

Novel Hadrons

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Fermilab

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Hadronic Physics . . .

strong interactions (QCD) where strong

Past three years:

- ▷ Many new states, possibly of a new character
- ▷ incisive measurements
- ▷ lively conversation between theory and experiment
- ▷ particle / nuclear interface

Hadrons are different . . .

. . . from everyday forms of matter

proton mass $\neq \sum$ constituent masses

QCD: $M_{\text{proton}} \approx$ confinement energy

(quark masses hardly contribute)

~ explains nearly all visible mass of Universe

Quark model: sound organizing principle

Quantum numbers fit two standard body plans:

Baryons: qqq

Mesons: $q\bar{q}$

$u, d, s, c, b, [t]$

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antisymmetric wave functions \leadsto color

+ confinement / parton model “paradox” \leadsto QCD

QCD: color singlets energetically favored
vacuum is a dia-electric medium

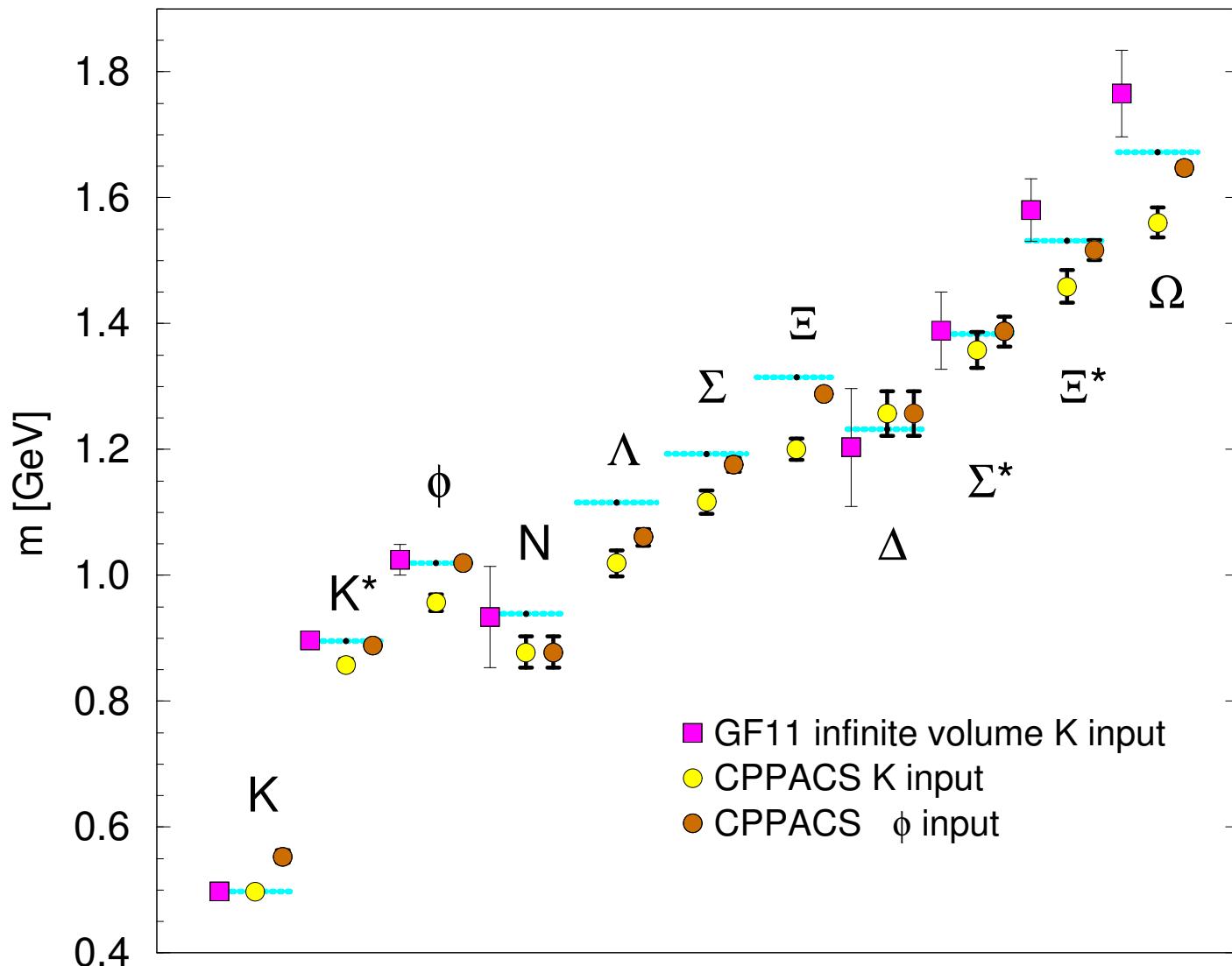
no assurance that only $q\bar{q}$ or qqq

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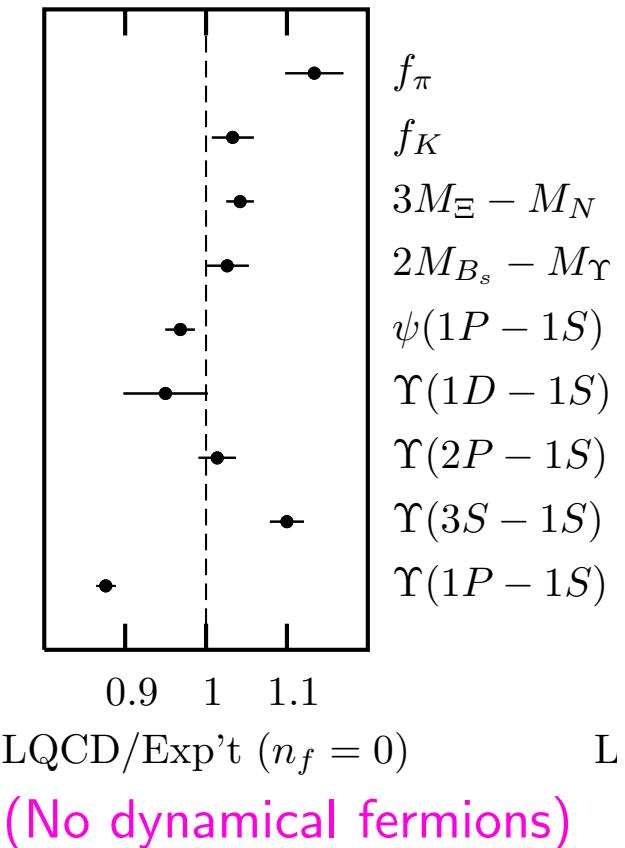
$$\text{SU}(3)_c \rightarrow \text{SU}(N)_c, N \rightarrow \infty$$



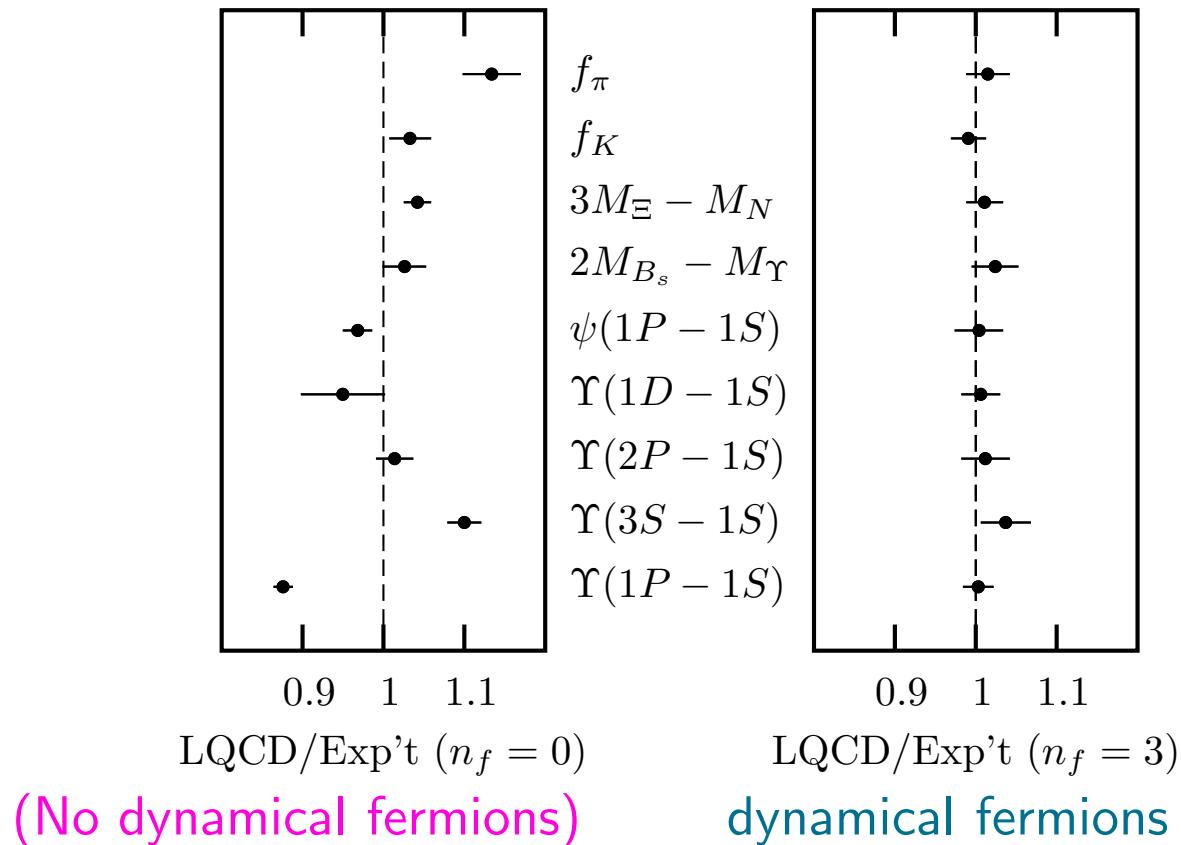
S. Aoki, et al. (CP-PACS)

(No dynamical fermions)

Lattice vs. experiment



Lattice vs. experiment



Seeking the Relevant Degrees of Freedom

Under what circumstances are diquarks useful / essential?

Correlations among quarks long known . . .

- ▷ $x \rightarrow 1$ behavior of proton parton distributions:
 - $F_2^n/F_2^p \not\rightarrow \frac{2}{3}$
 - Spin differs from SU(6) wave functions
- ▷ $\mathbf{3} \otimes \mathbf{3}$ attractive in $\mathbf{3}^*$ (half as strong as in $\mathbf{3} \otimes \mathbf{3}^* \rightarrow \mathbf{1}$?)
- ▷ Scalar nonet $f_0(600) = \sigma, \kappa(900), f_0(980), a_0(980)$ as $qq\bar{q}\bar{q}$ organized into diquark–antidiquark $\mathbf{3} \otimes \mathbf{3}^*$

Chew–Frautschi systematics for N, Δ

Selem & Wilczek

If light baryons are usefully viewed as $q[qq]_{3^*} \dots$

Test and extend the idea:

- $\sim QQq$ baryons (and comparison with $Q\bar{q}$)
- systematics of $qq \cdot \bar{q}\bar{q}$ states; extension to $Qq \cdot \bar{Q}\bar{q}$ states
- shape of baryons (at least high-spin?) in lattice QCD
- comparison with $1/N_c$ systematics?
- configurations beyond qqq and $\bar{q}q$?
- role of diquarks in color–flavor locking, color superconductivity, etc.
- colorspin as an organizing principle? mass effects ...

Exotic Baryons (Pentaquarks)

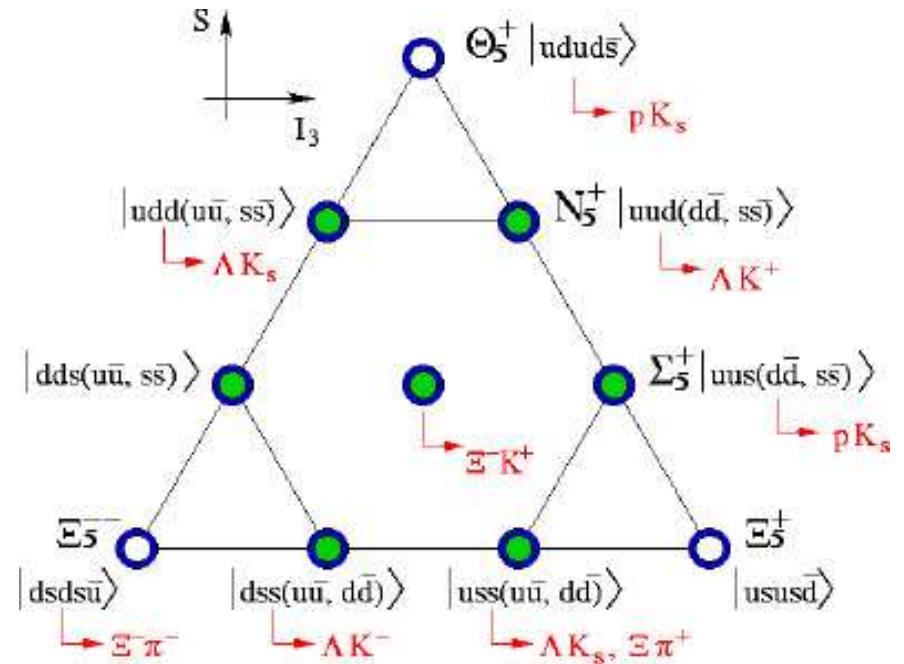
Claims for narrow exotic baryons:

$\Theta^+(\approx 1540)$: many sightings . . .

$\Theta^{++}(1530)$: STAR

$\Xi^{--}, 0(1862)$: NA49

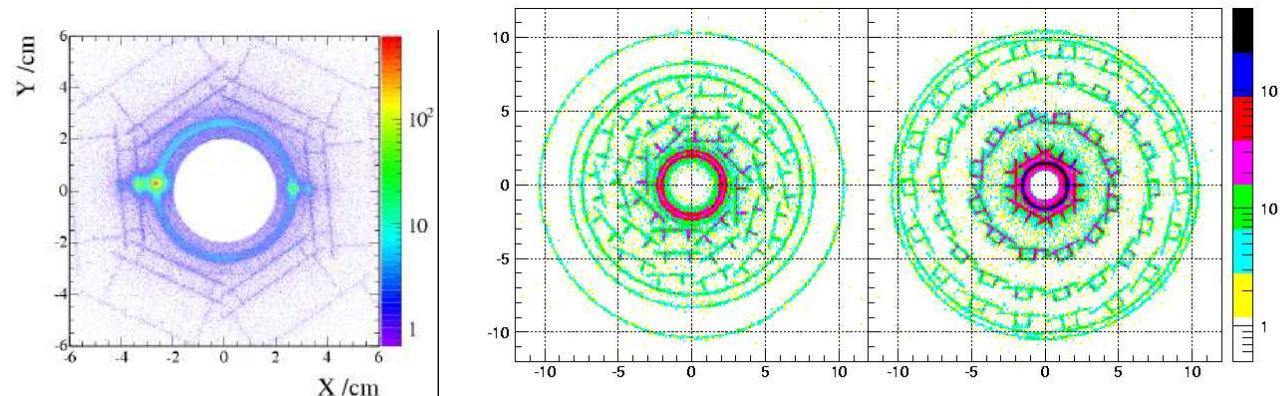
$\Theta_c^0(3099)$: H1

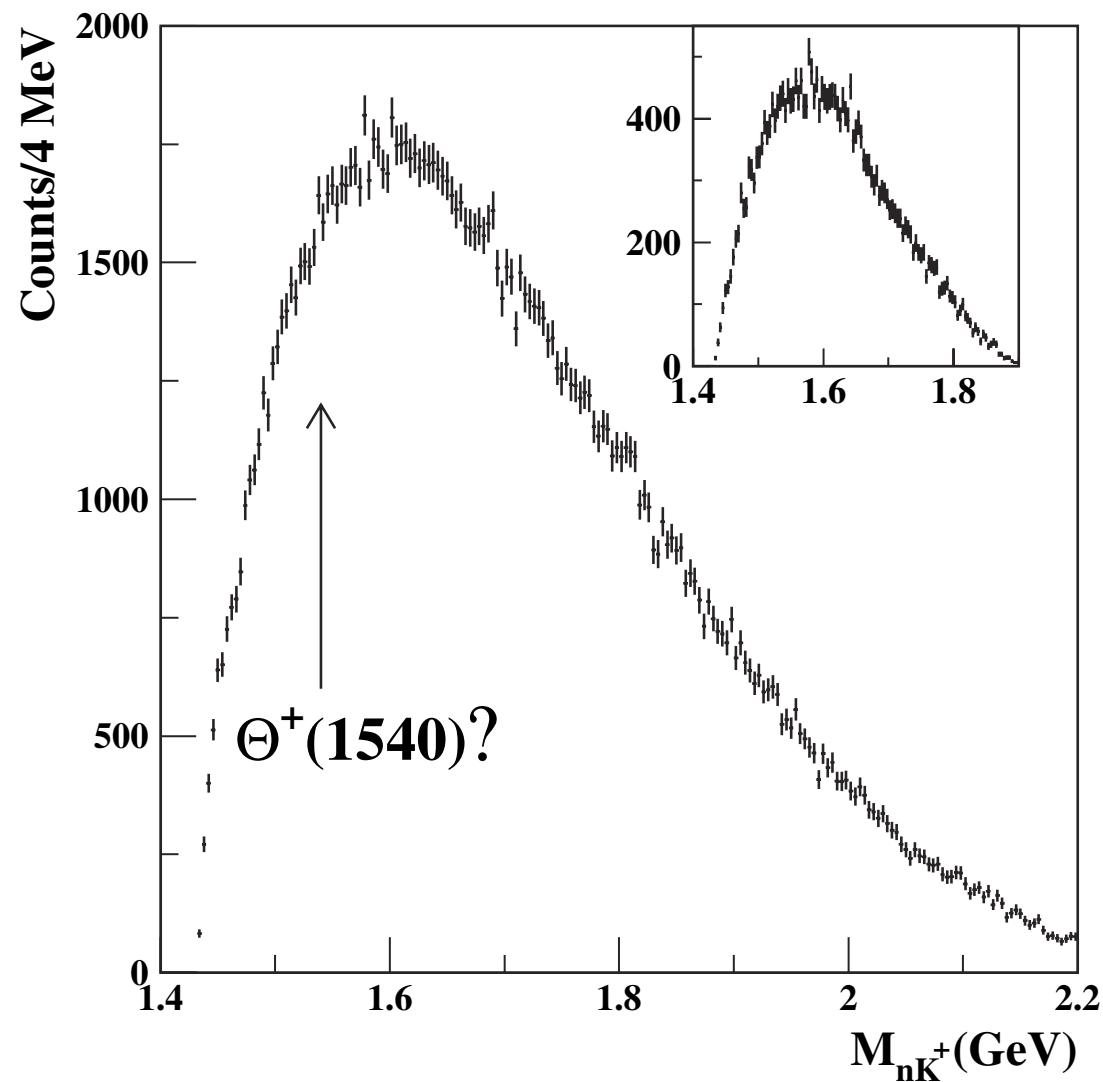


No claim is unchallenged!

Hard to argue that every experiment is significant, correctly interpreted.

- CLAS (JLab) $\gamma p \rightarrow K_S K^+ n$: ~ 1500 counts / 4-MeV bin: no signal
- CLAS (JLab) $\gamma d \rightarrow K^- p K^+ n$: no signal; increased estimate of background reduces significance of original claim to $\sim 3\sigma$
- DELPHI limits in Z decay
- HERA-B no observation of Θ^+ , Ξ^{--}
- Status reports on H1, ZEUS
- BaBar & Belle interactions with detector elements



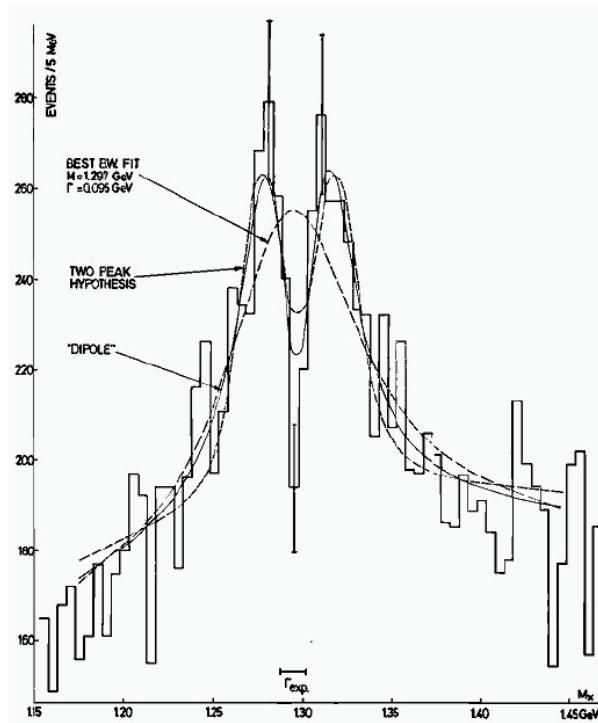


JLab

The case for exotic baryons remains unproved . . .

Details: V. Burkert @ Uppsala

“Split A_2 ”

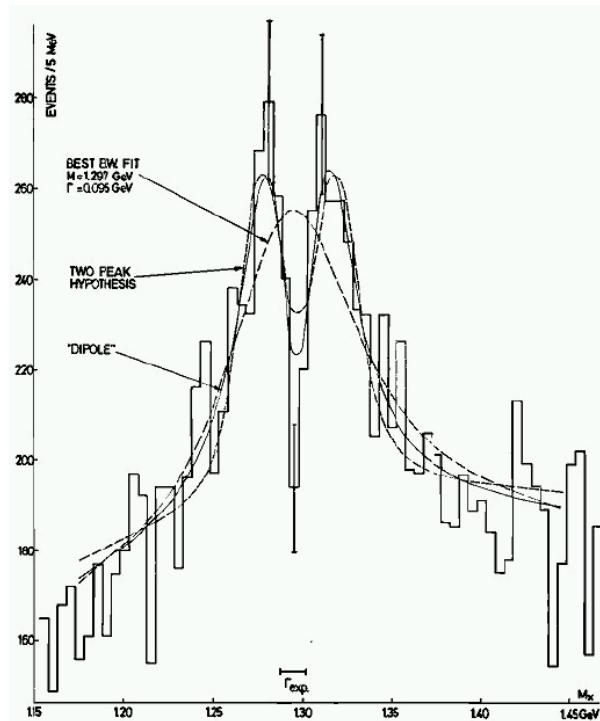


. . . 1969 Lund Conference

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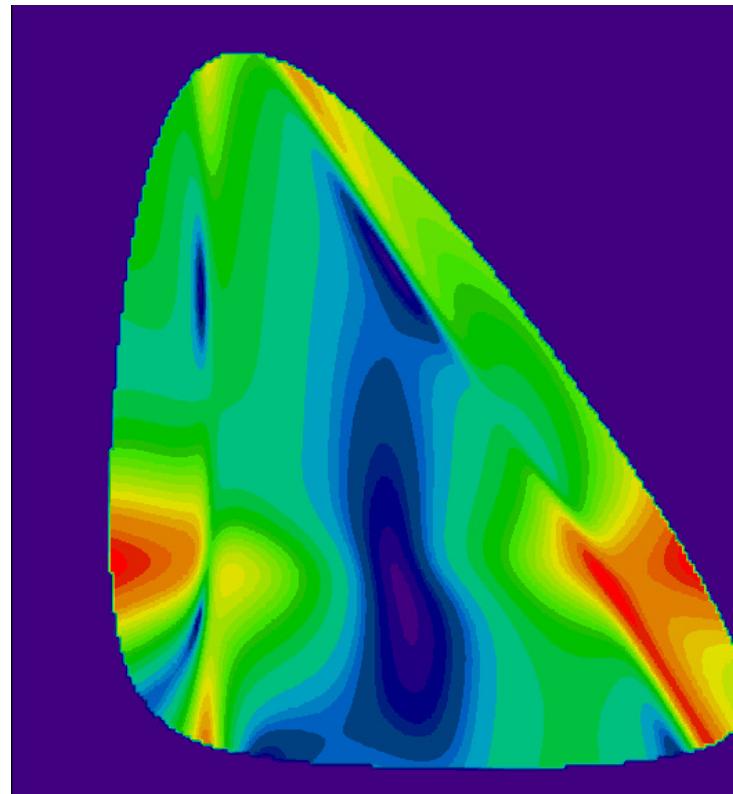
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“It is a part of probability that many improbable things will happen.”

George Eliot (after Aristotle), *Daniel Deronda*

Dalitz-Plot Analyses

Access to amplitudes and phases



$$(D^0 \rightarrow K^- \pi^+ \pi^0)$$

CLEO-*c* goal: determine strong phase between $D^0 \rightarrow K^\pm K^{*\mp}$ for extraction of $\phi_3 = \gamma$ from $B^\pm \rightarrow K^\pm K^{*\mp} K^\pm$

Stretching our models, calculations

Leaving the comfort zone, looking for unseen effects
Extend descriptions of ψ, Υ to B_c

$B_c \rightarrow \pi J/\psi, a_1 J/\psi, J/\psi \ell \nu$

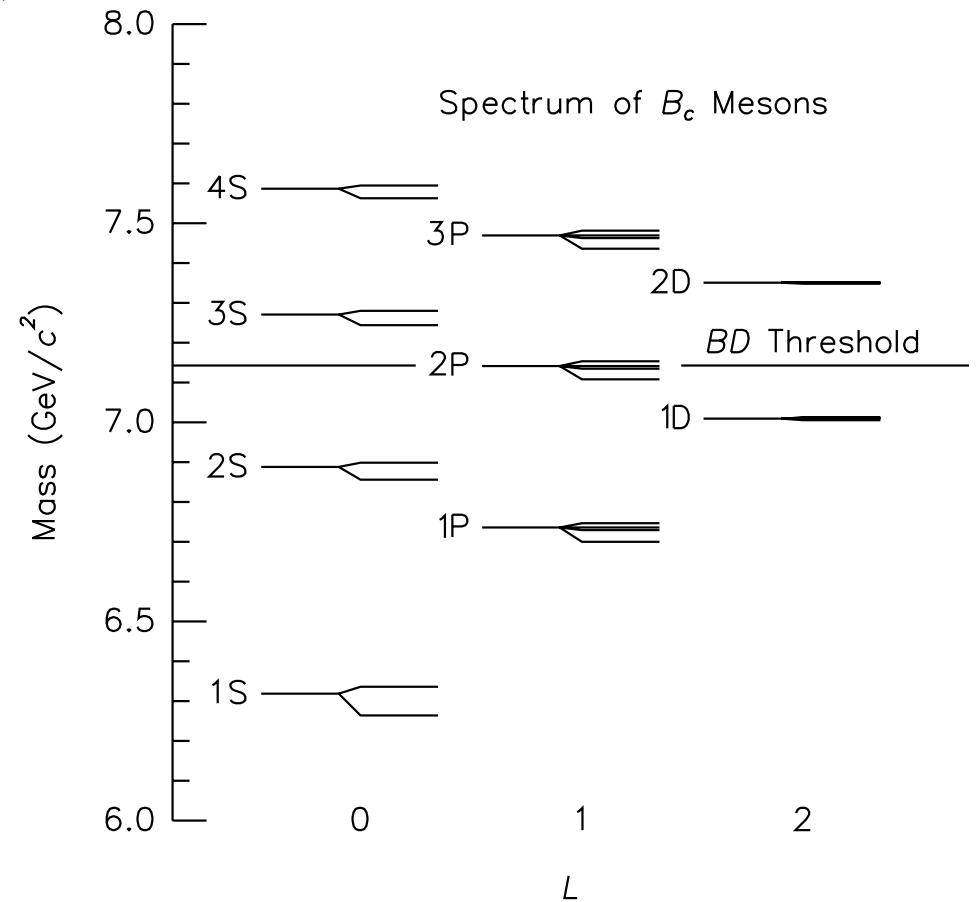
hadronic, γ cascades to B_c

interpolates $Q\bar{Q}$, $Q\bar{q}$, but c more relativistic than in $c\bar{c}$,
unequal-mass kinematics:
 \sim enhanced sensitivity
to effects beyond NRQM?

CDF: $M(B_c) = 6286 \pm 6$ MeV

$\sim 6275.2 \pm 4.5$ MeV

Lattice: 6304 ± 20 MeV



Quarkonium Spectroscopy

A flood of beautiful new results

- CLEO discovery of $h_c(1^1P_1)$ in $\psi' \rightarrow \pi^0 h_c$
 $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV $\approx \langle M(1^3P_J) \rangle - 1$ MeV
- Belle $\gamma\gamma \rightarrow \eta_c, \chi_{c0}, \chi_{c2} \rightarrow h^+h^-, h^+h^-h^+h^-$
rates $\Gamma(\eta_c \rightarrow \gamma\gamma)\mathcal{B}(\eta_c \rightarrow f)$ about $1/3 \times$ PDG rates
- CLEO observation of $\psi(3770) \rightarrow \pi\pi J/\psi$
 $\mathcal{B}(\psi(3770) \rightarrow \pi^+\pi^- J/\psi) = (189 \pm 22^{+7}_{-4}) \times 10^{-5}$
and $\Gamma(\psi(3770) \rightarrow \gamma\chi_{c1}) = 78 \pm 19$ keV
- CLEO $\mathcal{B}(\Upsilon(5S) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}) = 16.0 \pm 2.6 \pm 6.3\%$
 $\Gamma(\Upsilon(1S) \rightarrow e^+e^-) = 1.336 \pm 0.009 \pm 0.019$ keV (+ 2S,3S)

- **KEDR** $M(\psi') = 3686.117 \pm 0.012 \pm 0.015$ MeV
 $M(\psi(3770)) = 3773.5 \pm 0.9 \pm 0.6$ MeV
- **Belle** Observe $\Upsilon(4S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$
38 \pm 6.9 events, $\mathcal{B} = (1.1 \pm 0.2 \pm 0.4) \times 10^{-4}$
- **CLEO** Observe $\chi_b'(2^3P_{2,1}) \rightarrow \pi^+ \pi^- \chi_b(1^3P_{2,1})$
 $\Gamma \approx 0.9$ keV (first non- 3S_1 transition seen)

New states associated with charmonium *. . . the lost tribes of charmonium*

By 2002: 25 years since a new $c\bar{c}$ state . . .

☞ Over past three years . . .

η'_c and h_c below $D\bar{D}$ threshold

η''_c and χ'_{c2} above $D\bar{D}$ threshold

$X(3872)$, $Y(3940)$, $Y(4260)$, . . .

Rare decays of $\psi(3770)$

New (more capable, more sensitive) experiments

New production channels: B decays, $\gamma\gamma$, $c\bar{c}c\bar{c}$, $gg \rightarrow c\bar{c}$

Eichten, Lane, CQ, *PRL* **89**, 162002 (2002); *PRD* **69**, 094019 (2004); *PRD* **73**, 014014 (2006)

The Lost Tribes of Charmonium

- ▷ $c\bar{c}$ states below $D\bar{D}$ threshold

$$1^1P_1 \ h_c, \ J^{PC} = 1^{+-}$$

$$2^1S_0 \ \eta'_c, \ J^{PC} = 0^{-+}$$

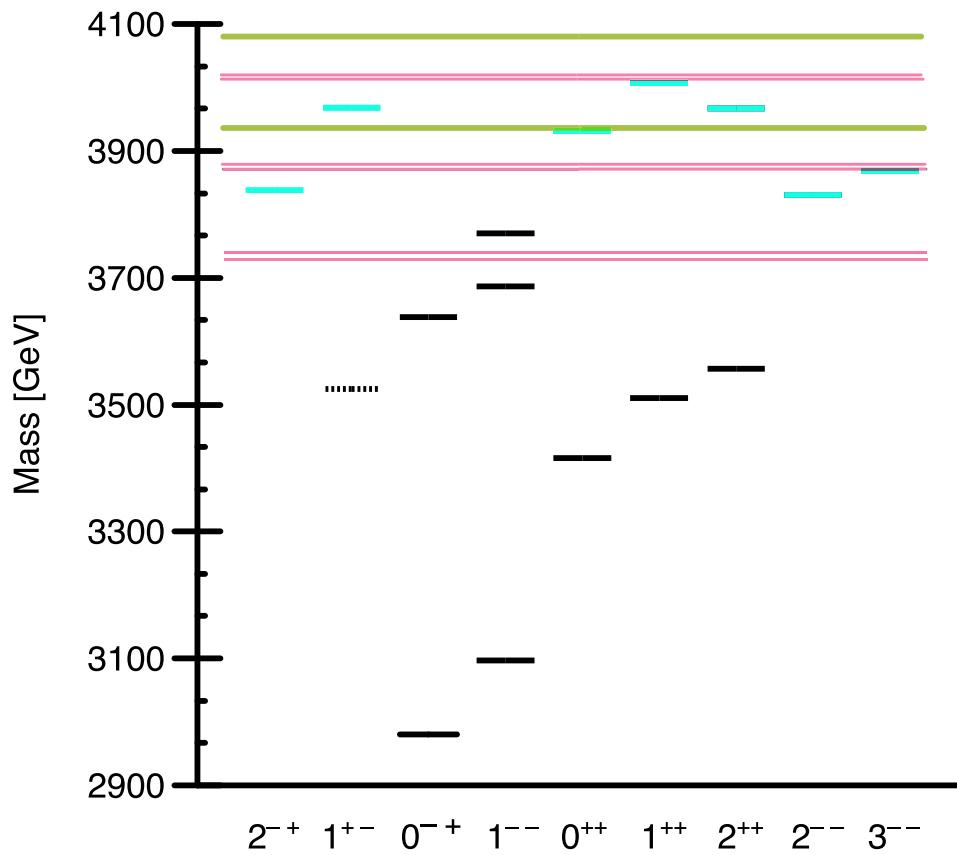
- ▷ Unnatural parity $c\bar{c}$ states between $D\bar{D}$ and $D\bar{D}^*$ thresholds

$$1^1D_2 \ \eta_{c2}, \ J^{PC} = 2^{-+}$$

$$1^3D_2 \ \psi_2, \ J^{PC} = 2^{--}$$

- ▷ Narrow $c\bar{c}$ states decaying to open charm

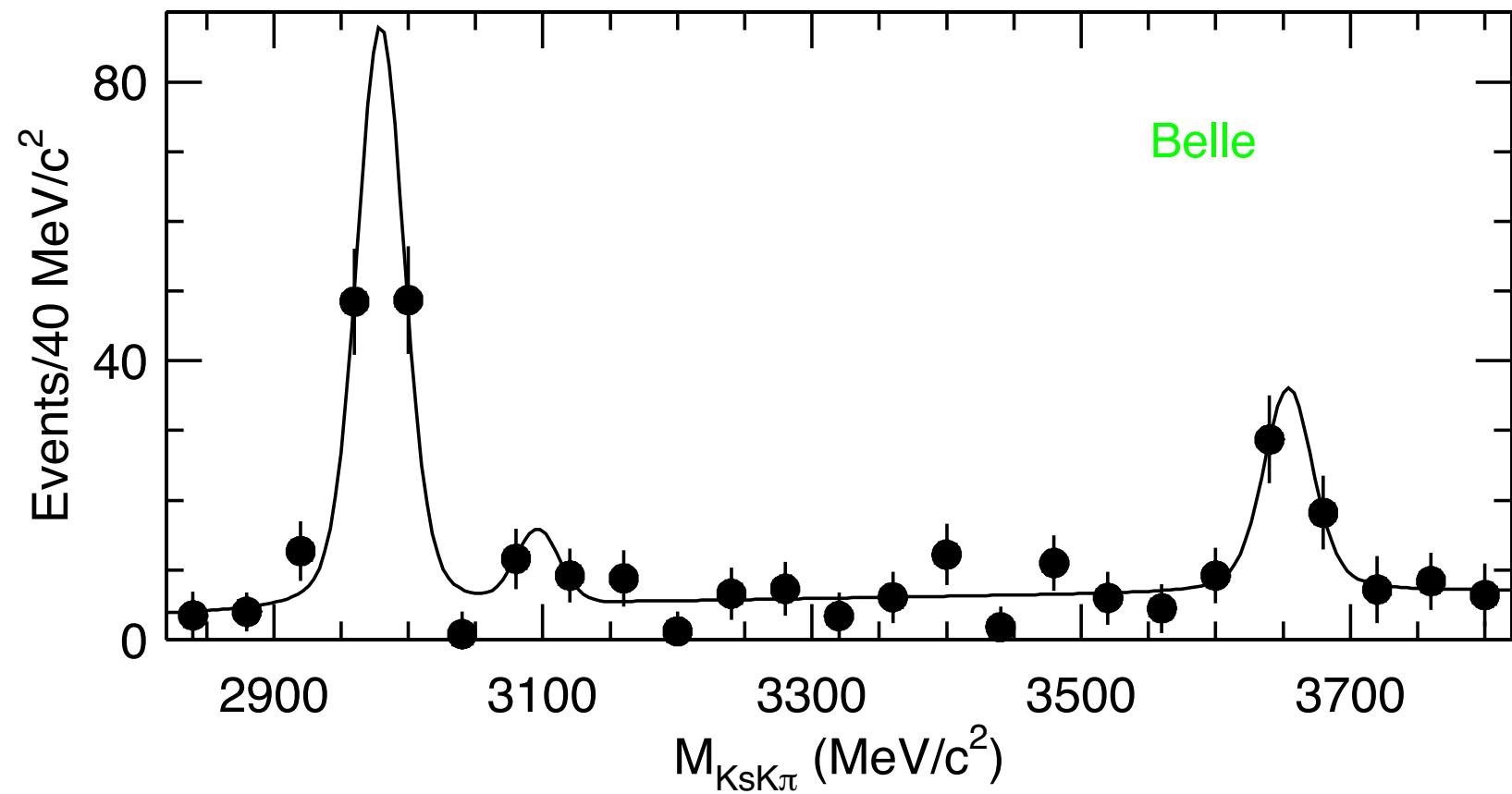
$$1^3D_3, 2^3P_2, 1^3F_4, \dots$$



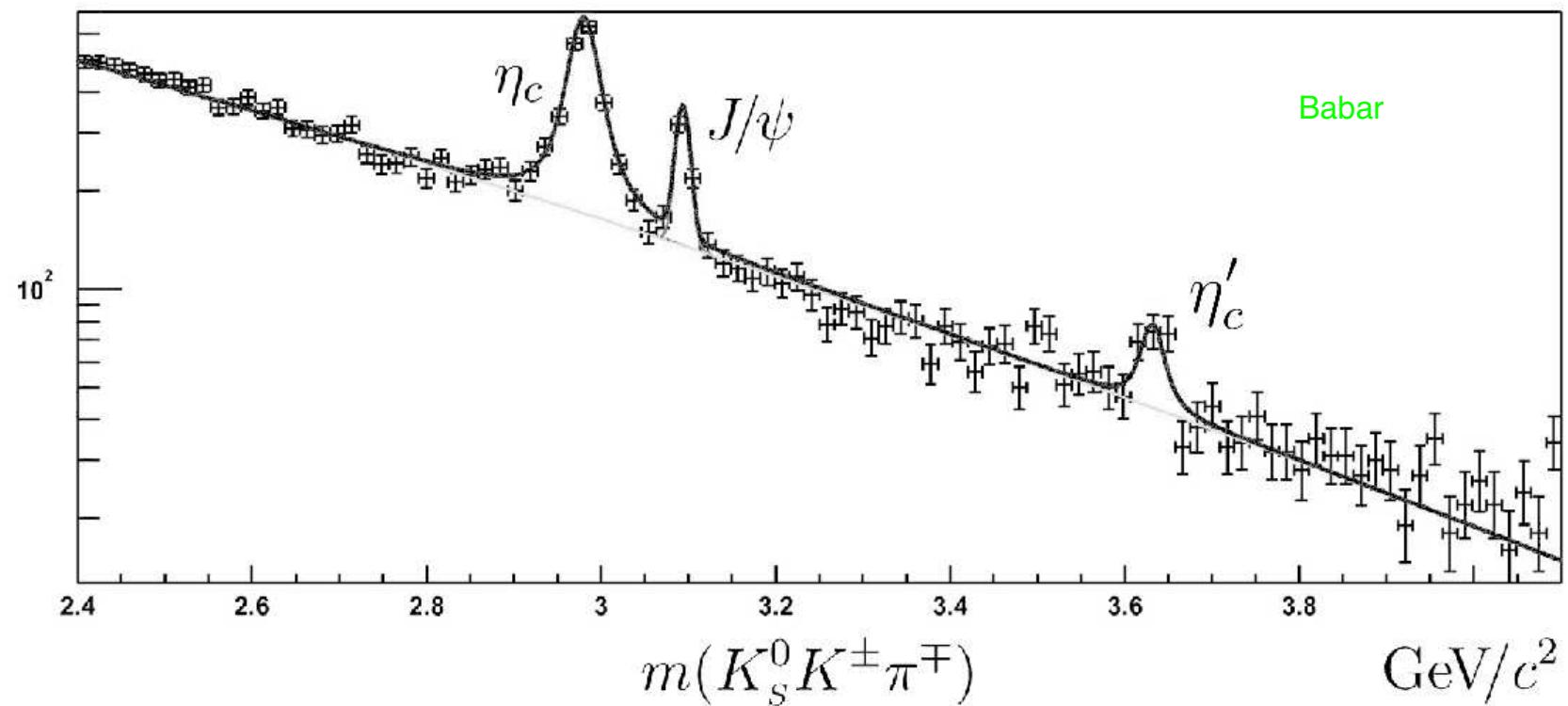
Many states to study; more to QCD than potential models . . .

New J^{PC} accessible; compare Υ , B_c

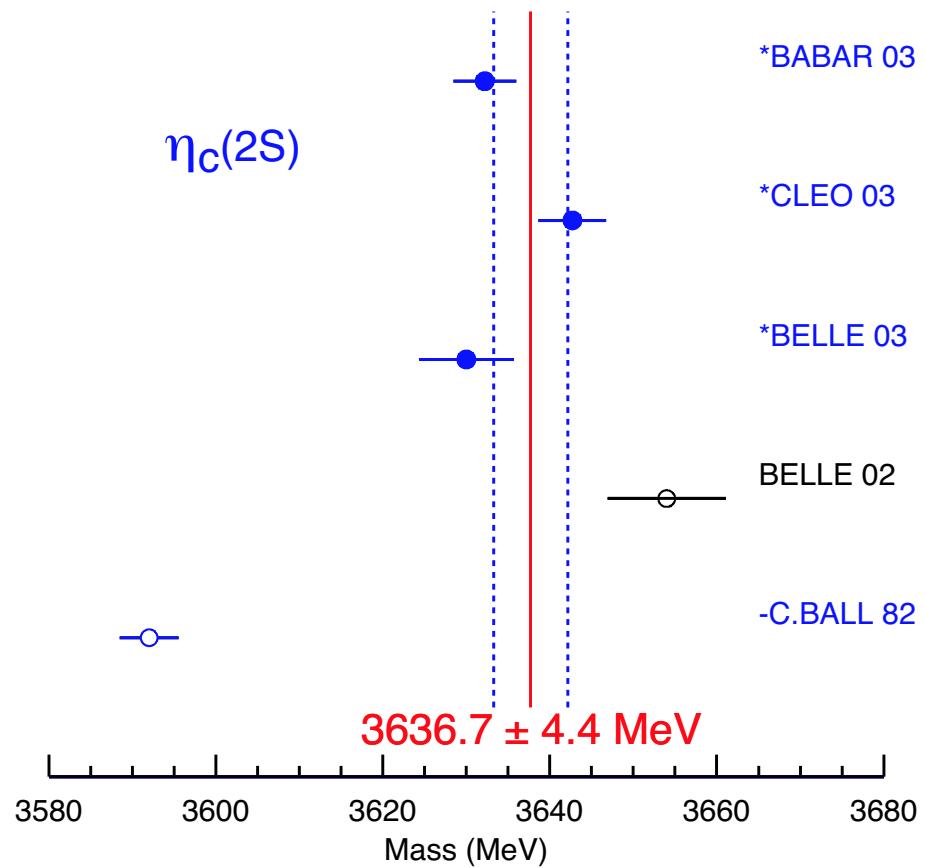
Discovery of η'_c 2^1S_0 in $B \rightarrow K K_S K^\mp \pi^\pm$ Belle



η'_c confirmation in $\gamma\gamma \rightarrow K_S K^- \pi^+$ BaBar, CLEO, Belle



$$M(\psi') - M(\eta'_c) = (48.3 \pm 4.4) \text{ MeV}$$



CLEO III Search for h_c in $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$

- ▷ Inclusive (no η_c decays reconstructed):

$$M(h_c) = 3524.8 \pm 0.7 \pm (\sim 1) \text{ MeV}$$

$$B(\psi' \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c) \approx 4 \pm 2 \times 10^{-4}$$

significance $> 3\sigma$

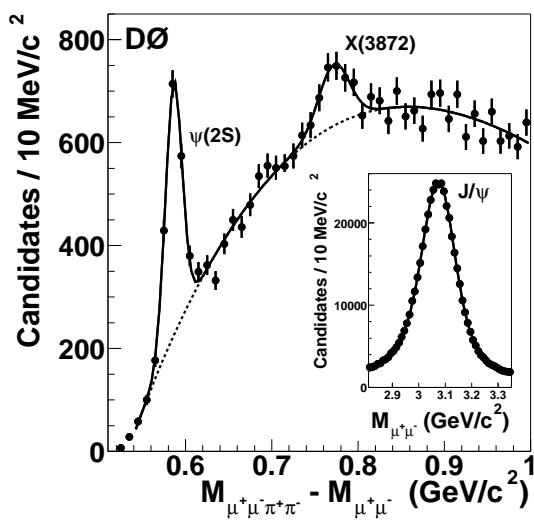
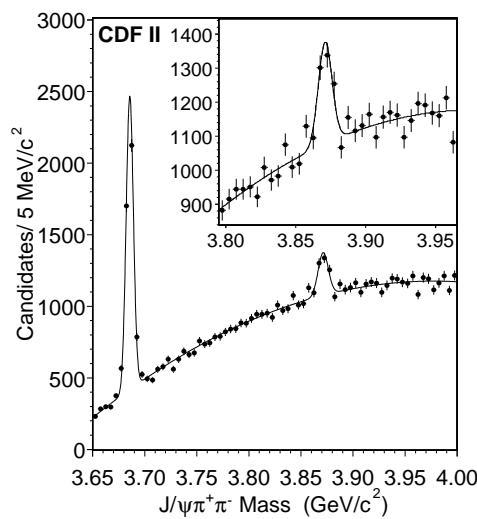
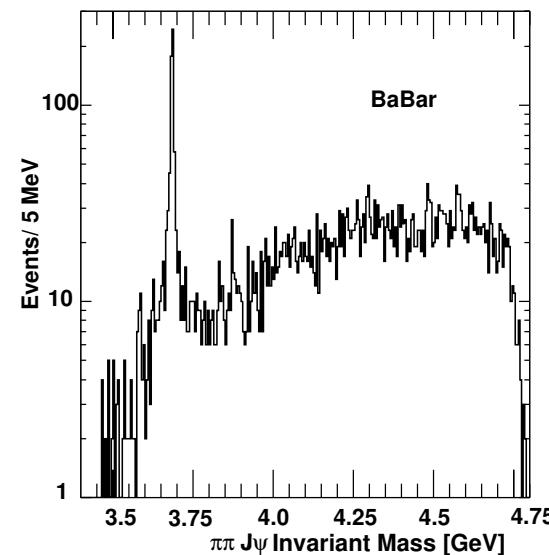
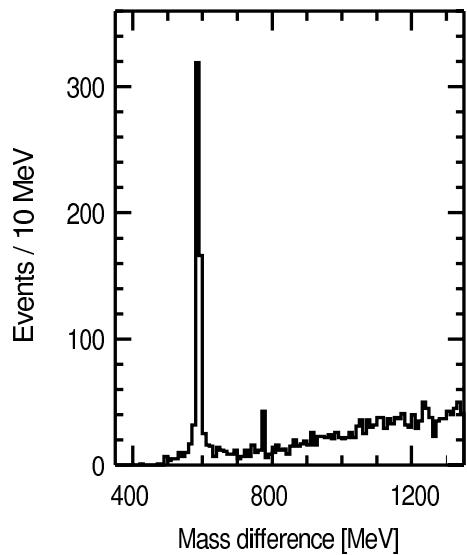
- ▷ Exclusive search (six hadronic decays of η_c):

$$M(h_c) = 3524.4 \pm 0.9 \text{ MeV}$$

significance $> 5\sigma$

A. Tomaradze, QWGIII · Beijing

$X(3872) \rightarrow \pi^+ \pi^- J/\psi$



$$X(3872) \rightarrow \pi^+ \pi^- J/\psi$$

Experiment	Sample	Events	Mass (MeV)	$M_{\pi\pi}$ cut
Belle	152M $\Upsilon(4S) \rightarrow B\bar{B}$	35.7 ± 6.8	3872.0 ± 0.8	plot
CDF	220 pb^{-1}	730 ± 90	3871.4 ± 0.8	500 MeV
DØ	230 pb^{-1}	522 ± 100	3871.8 ± 4.3	520 MeV
BaBar	117M $\Upsilon(4S) \rightarrow B\bar{B}$	25.4 ± 8.7	3873.4 ± 1.4	plot

$$3871.9 \pm 0.6$$

(Compare $D^0 \bar{D}^{*0}$ threshold, 3871.5 MeV)

$\bar{p}p$ rates, ψ' comparison \leadsto appreciable prompt production

$$\Gamma(X \rightarrow \text{all}) < 2.3 \text{ MeV (Belle)}$$

Natural prejudice: 3D_2 $c\bar{c}$ state, $J^{PC} = 2^{--}$

But:

▷ Mass is higher than expected:

3815 MeV in one-channel potential model

▷ Expected prominent (dominant) radiative decays

$$\text{Belle: } \frac{\Gamma(X(3872) \rightarrow \gamma \chi_{c1,2})}{\Gamma(X(3872) \rightarrow \pi^+ \pi^- J/\psi)} < 0.89, 1.1$$

Normalization requires measurement of

$$\Gamma(\psi(3770) \rightarrow \pi \pi J/\psi)$$

(All $\Gamma({}^3D_J \rightarrow \pi \pi \psi)$ equal by Wigner–Eckart)

BES II: (85 ± 35) keV CLEO: < 55 keV

Natural prejudice: 3D_2 $c\bar{c}$ state, $J^{PC} = 2^{--}$

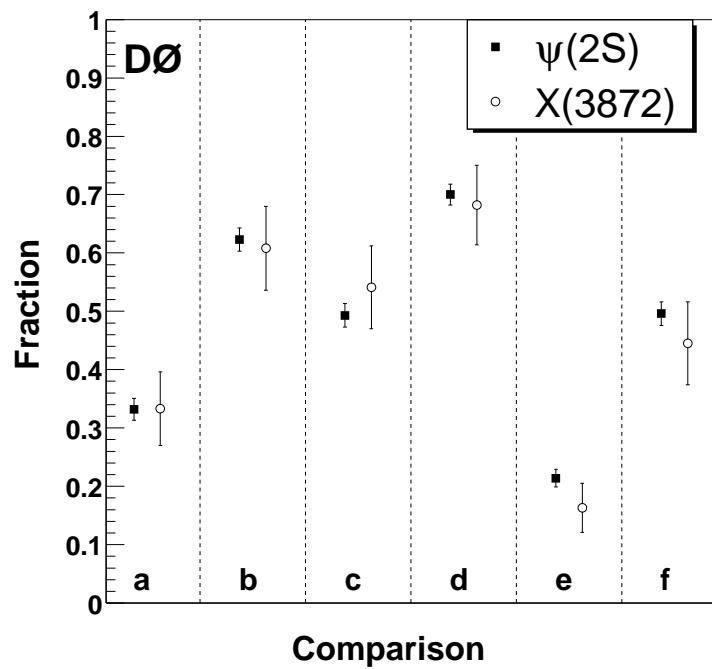
Alternatives:

- ▷ $(D\bar{D}^*)$ threshold cusp in 1^{++} (*s*-wave) Bugg, hep-ph/0406293, 10168
- ▷ deuteron-like “molecules” formed by π exchange between D^0 and \bar{D}^{*0}
 - Most attractive: $J^{PC} = 0^{-+}, 1^{++}$ Törnqvist, hep-ph/0402237
 - Hadronic cascade must be $(\pi^+\pi^-)_{I=1} J/\psi$
 - Dissociation: $X \rightarrow (D^0\bar{D}^{*0})_{\text{virtual}} \rightarrow D^0\bar{D}^0\pi^0$
- ▷ $c\bar{c}g$ hybrid states Close & Godfrey, hep-ph/0305285
 - possibly enhanced $X \rightarrow \eta J/\psi, \sigma J/\psi, \gamma q\bar{q}, \gamma s\bar{s}$ Li, hep-ph/0410264
 - But lattice: $0^{+-}(4.7 \text{ GeV}), 1^{-+}(4.3 \text{ GeV}), 2^{+-}(4.9 \text{ GeV})$ Liao & Manke, hep-lat/0210030
- ▷ Other charmonium levels Pakvasa & Suzuki, hep-ph/0309294
 - Barnes & Godfrey, hep-ph/0311162
 - ELQ, hep-ph/0401210

X production in B decay ...

$$\frac{\mathcal{B}(B^- \rightarrow K^- X) \mathcal{B}(X \rightarrow \pi^+ \pi^- J/\psi)}{\mathcal{B}(B^- \rightarrow K^- \psi') \mathcal{B}(\psi' \rightarrow \pi^+ \pi^- J/\psi)} = \begin{cases} 0.063 \pm 0.014 & \text{Belle} \\ 0.059 \pm 0.020 & \text{BaBar} \end{cases}$$

$\bar{p}p$ collisions: $X(3872)$ responds as $\psi(2S)$



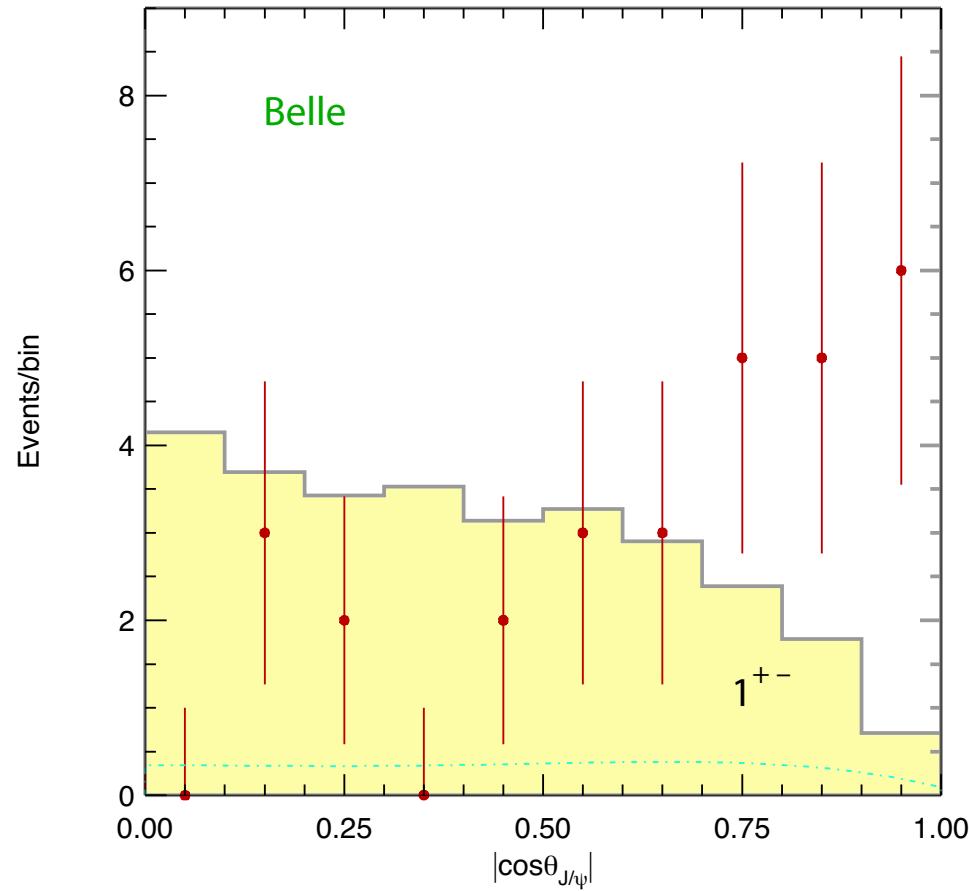
- (a) $p_t(\pi^+ \pi^- J/\psi) > 15$ GeV
- (b) $|y(\pi^+ \pi^- J/\psi)| < 1$
- (c) $\cos \theta_\pi < 0.4$
- (d) $dl < 0.01$ cm
- (e) isolation = 1
- (f) $\cos \theta_\mu < 0.4$

CDF: 16% $b \rightarrow X + \dots$ CDF-7159
 28% $b \rightarrow \psi' + \dots$

Where has X production *not* been seen?

- ▷ Radiative return from e^+e^- at $\sqrt{s} = 4.03$ GeV (BES):
 $\Gamma(X \rightarrow \ell^+\ell^-)\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 10$ eV (90% CL) [hep-ph/0310261](#)
... and from 15 fb^{-1} of CLEO III data [hep-ex/0410038](#)
 $\Gamma(X \rightarrow \ell^+\ell^-)\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 8.3$ eV (90% CL)
 $\sim \Gamma(X \rightarrow \ell^+\ell^-) < 0.35$ keV for $\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) > 2\%$
 $\Rightarrow 3^3S_1$ unlikely; doesn't encourage 1^{--}
- ▷ Untagged $\gamma\gamma$ fusion (CLEO III)
 $(2J+1)\Gamma(X \rightarrow \gamma\gamma)\mathcal{B}(X \rightarrow \pi^+\pi^-J/\psi) < 12.9$ eV (90% CL)
potentially sensitive to $0^{++}, 0^{-+}, 2^{++}, 2^{+-}, \dots$
- ▷ No charged partners found (BaBar) [hep-ex/0408083](#)
Isovector State Probability $< 1/600$

$X(3872) \rightarrow \pi^+ \pi^- J/\psi$ angular distribution disfavors 1^{+-}



$$dN/d\cos\theta_{J/\psi} \propto \sin^2\theta_{J/\psi} \text{ for } 1^{+-}$$

Enhanced $X \rightarrow \eta J/\psi?$

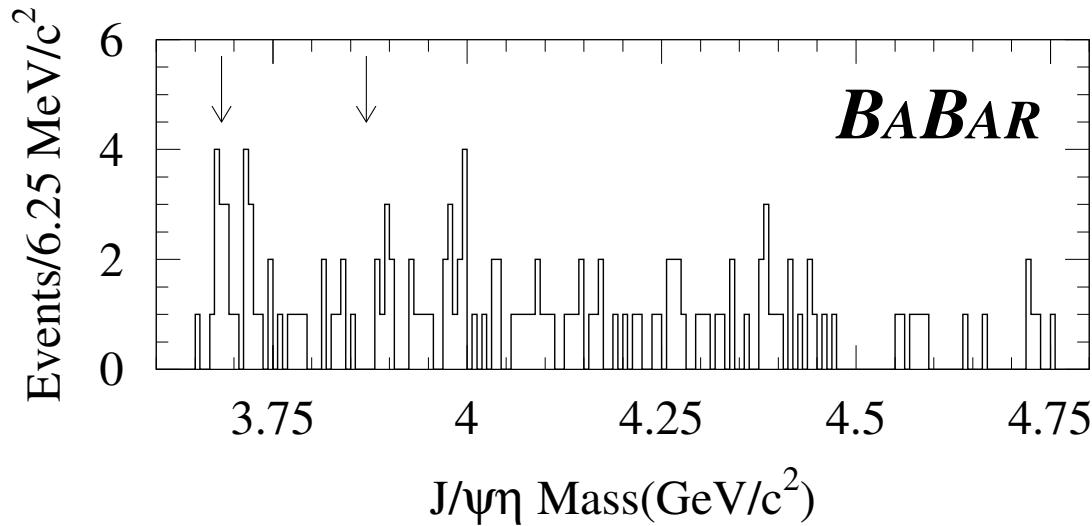


FIG. 3: The $J/\psi\eta$ mass distributions from $B^\pm \rightarrow J/\psi\eta K^\pm$ and $B^0 \rightarrow J/\psi\eta K_S^0$. The arrows indicate where the $\psi(2S)$ and $X(3872)$ signals would appear.

$$\mathcal{B}(B \rightarrow K^\pm X(3872), X \rightarrow \eta J/\psi) < 7.7 \times 10^{-6}, 90\% \text{ CL}$$

$< 2 \times \psi'$ rate \Rightarrow not enhanced

Coupling to open-charm channels

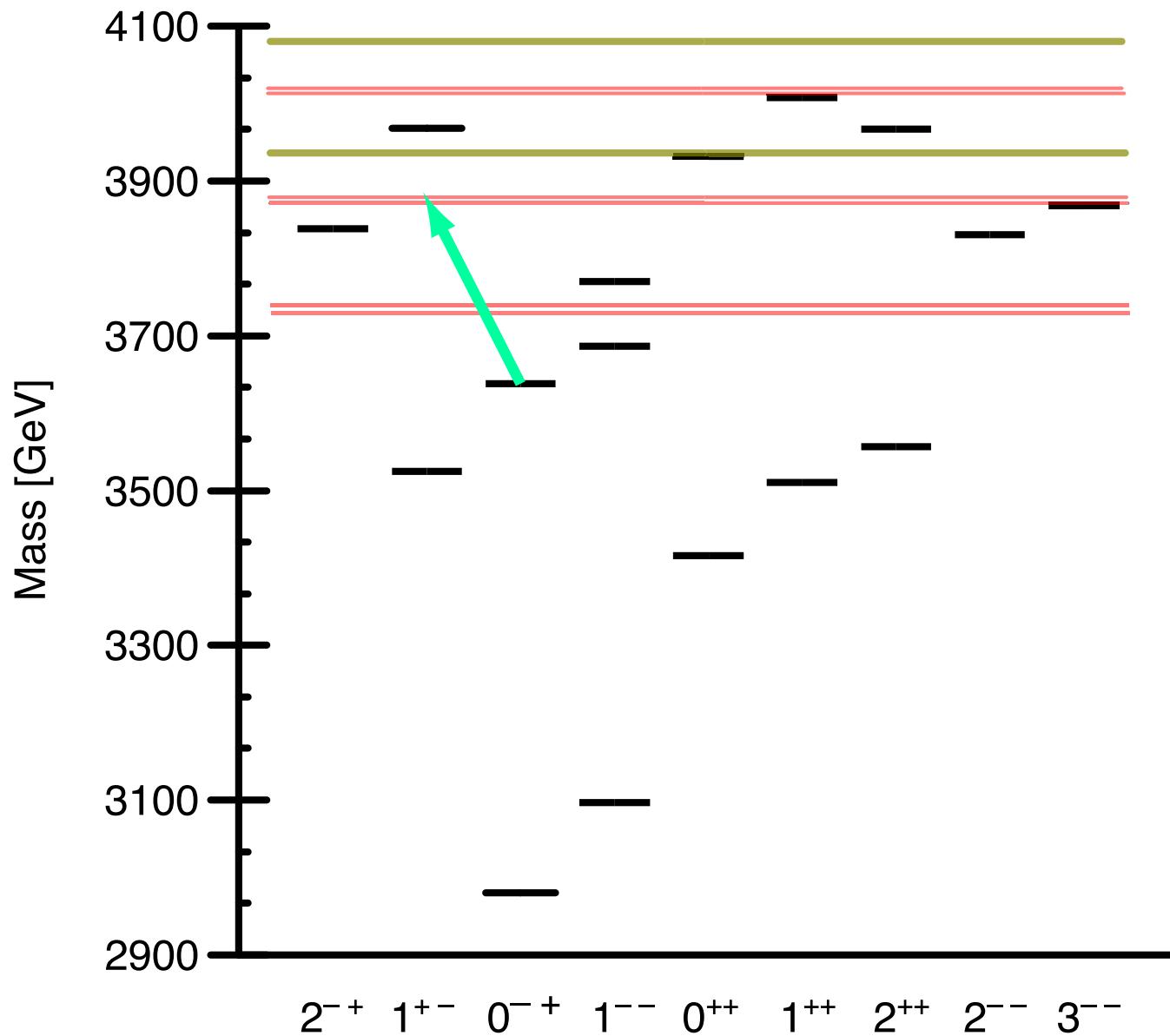
Phenomenological approach:

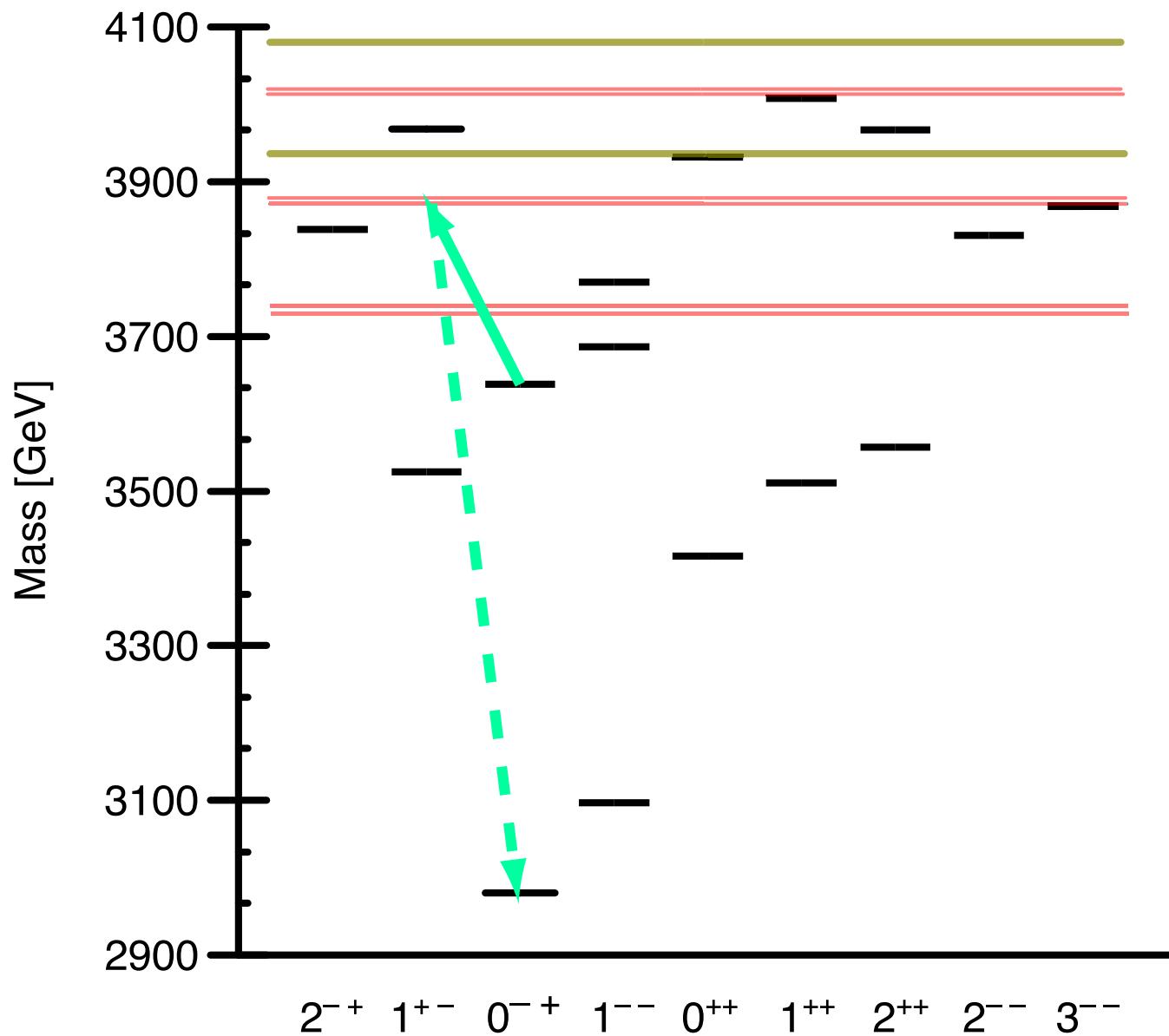
Evaluate $\langle n^3S_1 | \mathcal{H}_{\text{int}} | D\bar{D} \rangle$, etc.

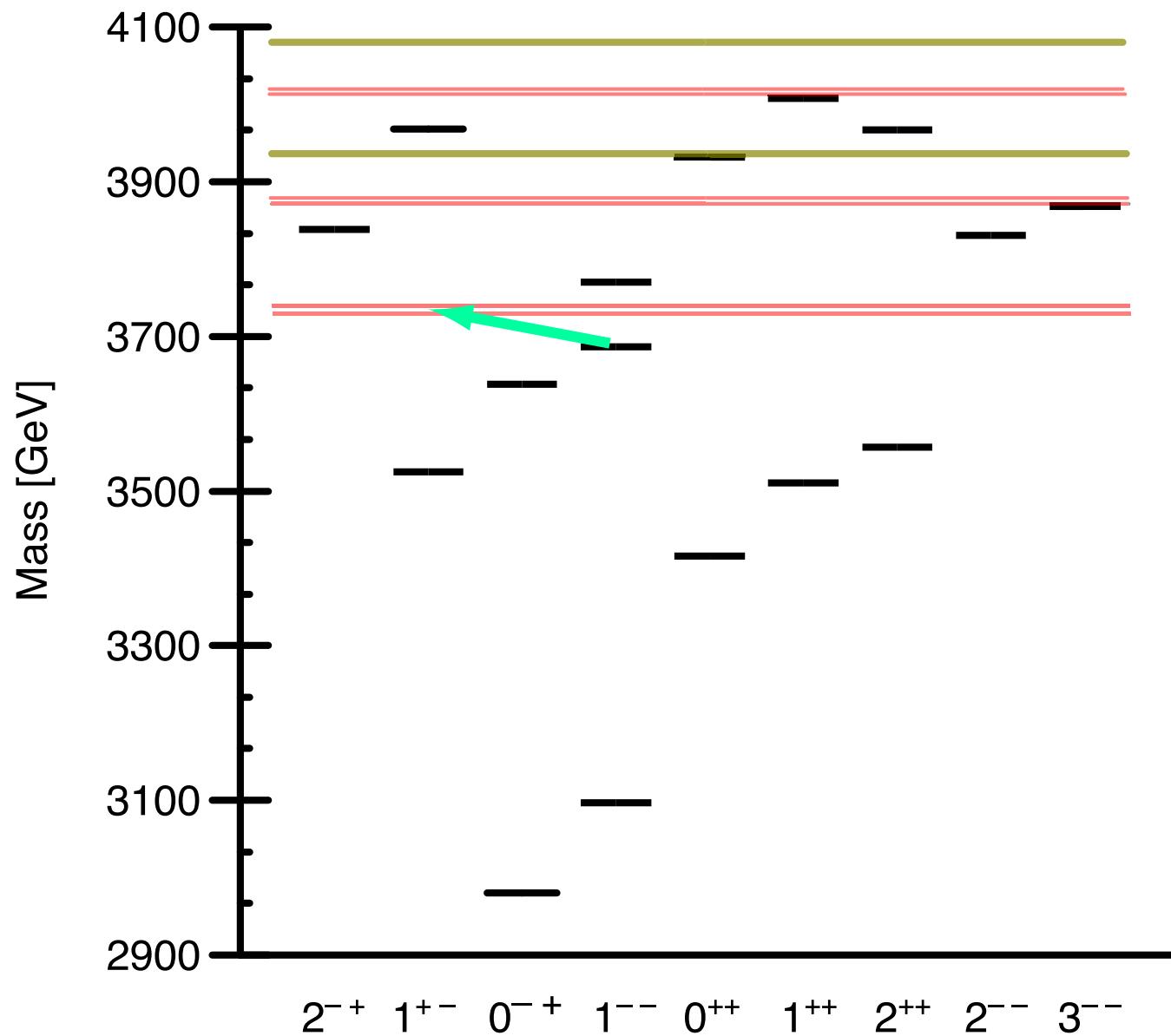
$$\mathcal{H}_{\text{int}} = \frac{3}{8} \int d\vec{x} d\vec{y} J_{0a}(\vec{x}) V(|\vec{x} - \vec{y}|) J_0^a(\vec{y})$$

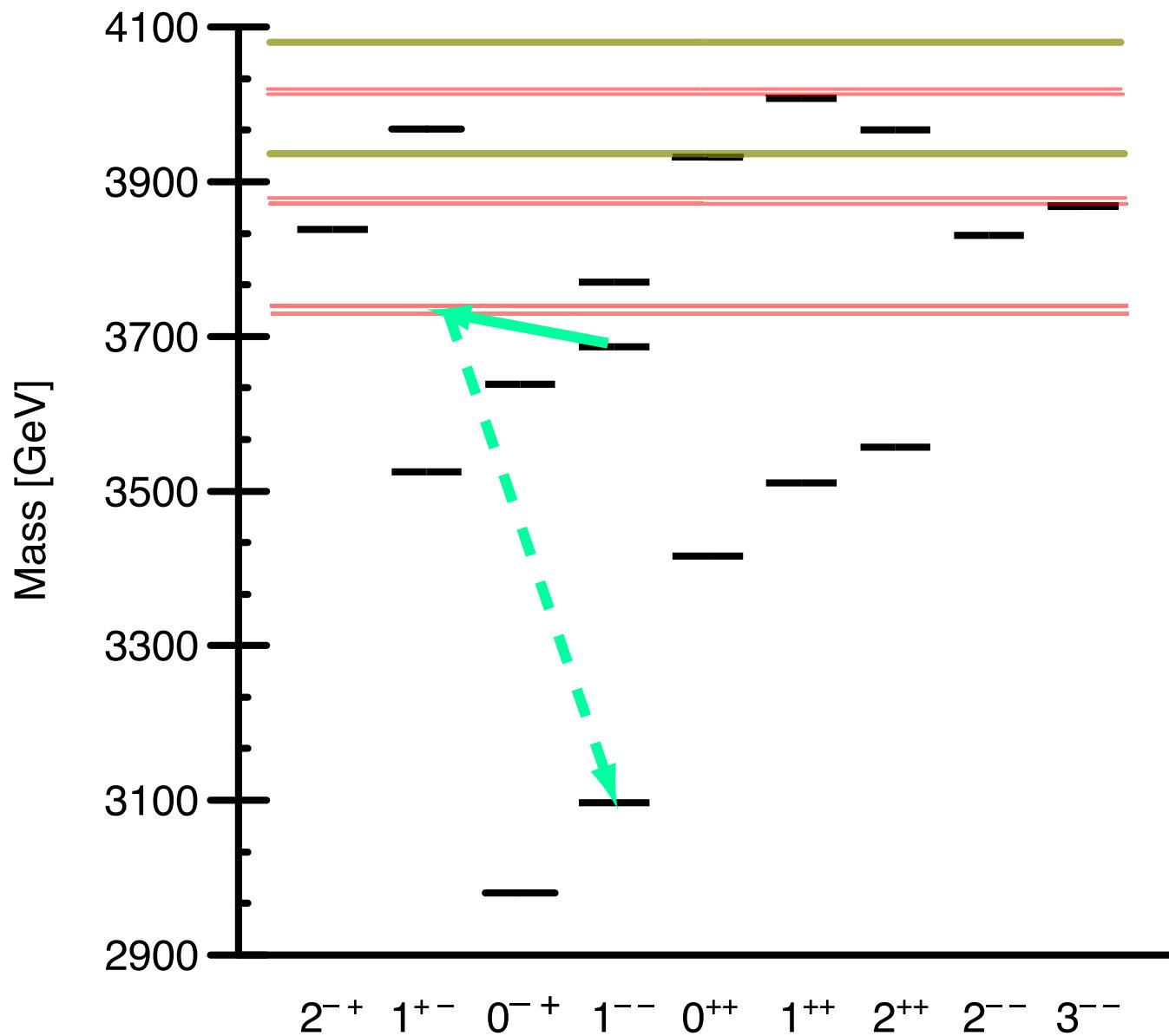
$$J_0^a(\vec{x}) = \frac{1}{2} (\bar{c}\gamma_0\lambda^a c + \bar{q}\gamma_0\lambda^a q)$$

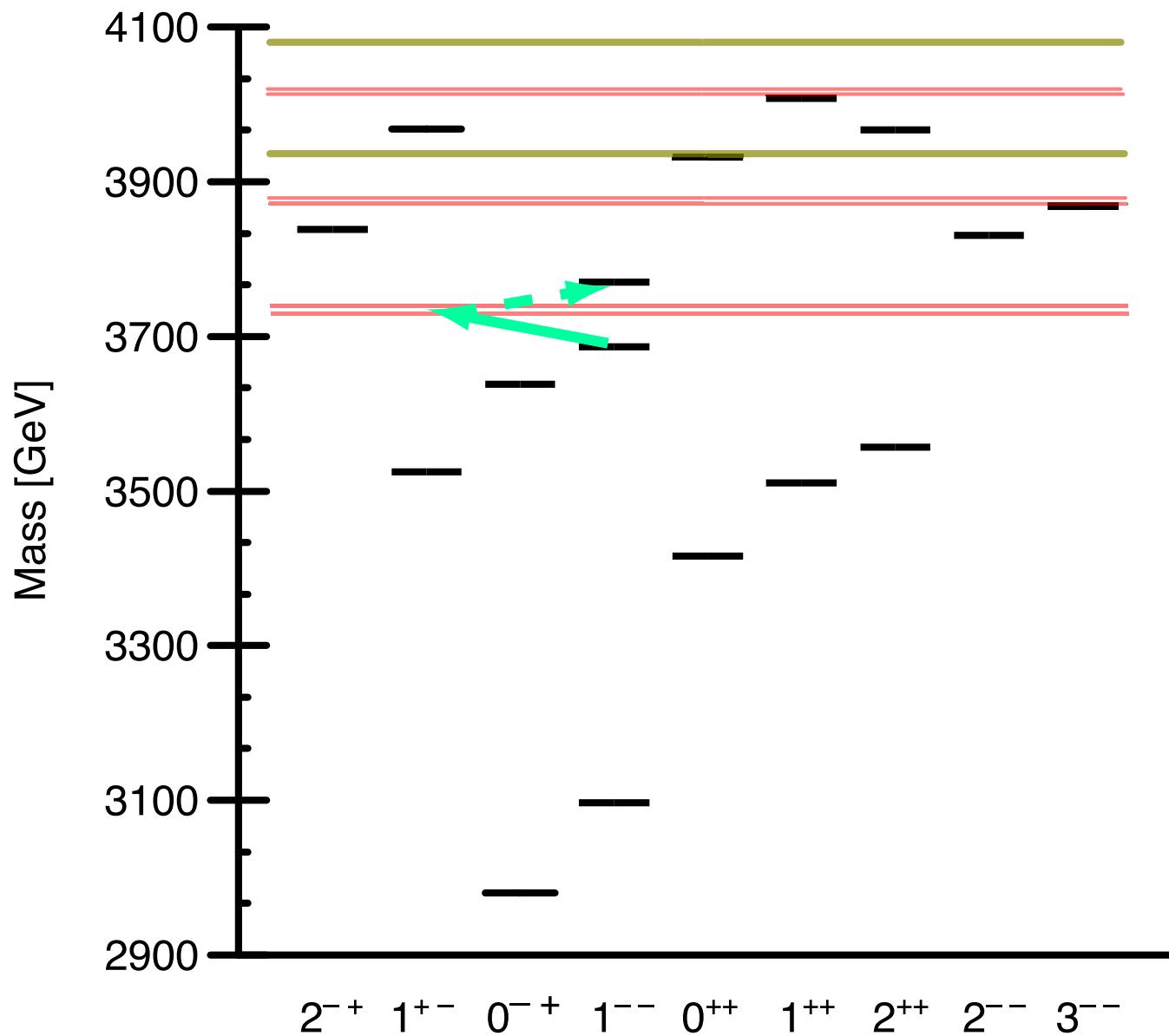
Calculate pair-creation amplitudes,
solve coupled-state system











Coupling to virtual channels induces spin-dependent forces . . .

State	Mass	Centroid	Splitting (Potential)	Splitting (Induced)
1^1S_0	2 979.9	3 067.6	-90.5	+2.8
1^3S_1	3 096.9		+30.2	-0.9
1^3P_0	3 415.3		-114.9	+5.9
1^3P_1	3 510.5	3 525.3	-11.6	-2.0
1^1P_1	3 525.3		+1.5	+0.5
1^3P_2	3 556.2		-31.9	-0.3
2^1S_0	3 637.7	3 673.9	-50.4	+15.7
2^3S_1	3 686.0		+16.8	-5.2
1^3D_1	3 769.9		-40	-39.9
1^3D_2	3 830.6	(3 815)	0	-2.7
1^1D_2	3 838.0		0	+4.2
1^3D_3	3 868.3		+20	+19.0
2^3P_0	3 931.9		-90	+10
2^3P_1	4 007.5	3 968	-8	+28.4
2^1P_1	3 968.0		0	-11.9
2^3P_2	3 966.5		+25	-33.1

$$M(\eta'_c) = 3637.7 \pm 4.4 \text{ MeV}$$

Hyperfine splitting:

$$M(\psi') - M(\eta'_c) = 32\pi\alpha_s |\Psi(0)|^2 / 9m_c^2$$

$$\text{Normalize to } M(\psi) - M(\eta_c) = 117 \text{ MeV}$$

$$\Rightarrow M(\psi') - M(\eta'_c) = 67 \text{ MeV}$$

$48.3 \pm 4.4 \text{ MeV}$ observed

20.9 MeV induced shift \Rightarrow agrees

Suppression of radiative decay rates

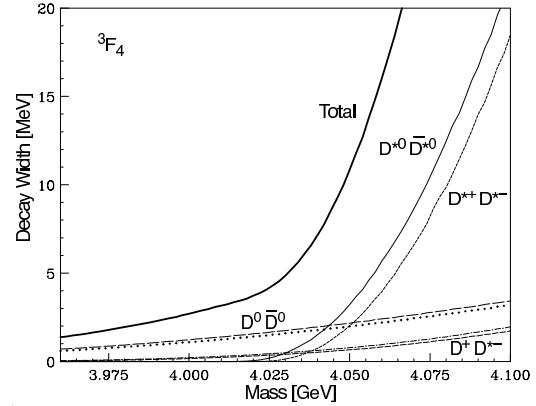
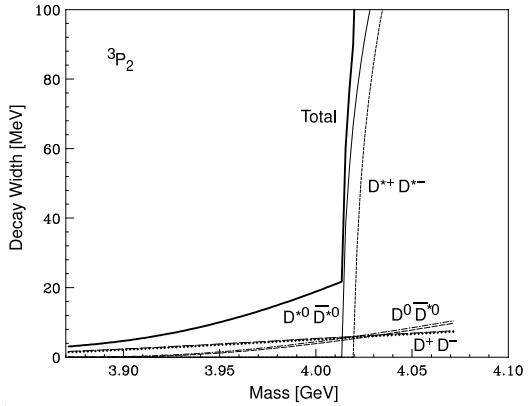
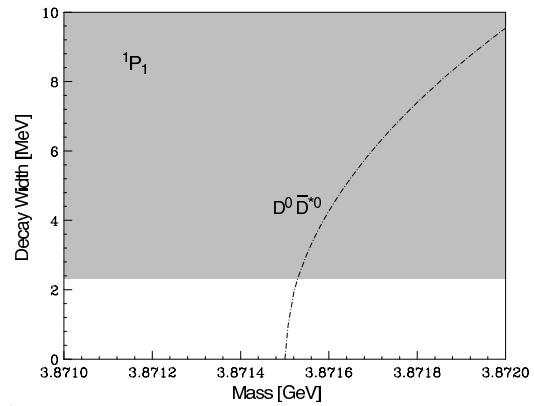
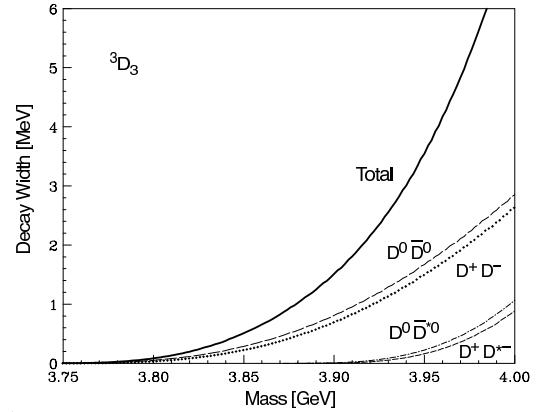
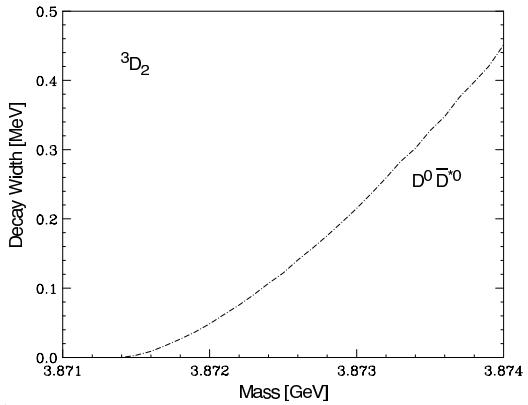
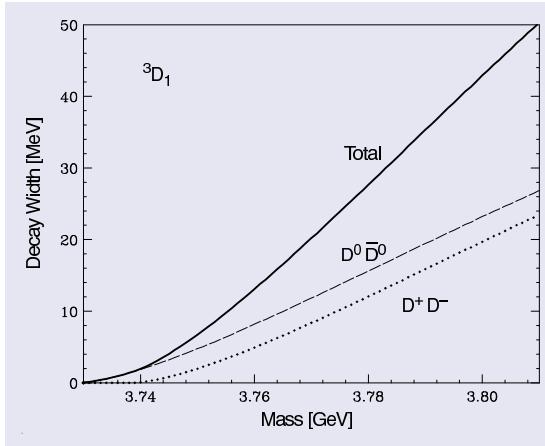
(reduced overlap between initial and final states)

$$\Psi(1^3D_2) = 0.754 |1^3D_2\rangle - 0.084 |2^3D_2\rangle - 0.011 |3^3D_2\rangle - 0.006 |4^3D_2\rangle + \dots$$

Transition (γ energy in MeV)	Partial width (keV)
$1^3D_2(3872) \rightarrow \chi_{c2} \gamma(303)$	$85 \rightarrow 45$
$1^3D_2(3872) \rightarrow \chi_{c1} \gamma(344)$	$362 \rightarrow 207$
$1^3D_3(3872) \rightarrow \chi_{c2} \gamma(304)$	$341 \rightarrow 299$

Decays into open charm

$$\Gamma(\psi'' \rightarrow D\bar{D}) = 20.1 \text{ MeV} \quad 23.6 \pm 2.7$$



What is $X(3872) \rightarrow \pi\pi J/\psi$?

- Candidate ψ_2 or ψ_3 , but no radiative decays seen
- $\pi\pi$ mass spectrum suggests $J/\psi \rho$ decay \rightsquigarrow not (pure) $I = 0$ $\pi^0\pi^0$?
- $J/\psi 3\pi$ decay suggests $J/\psi \omega$ decay
- $J/\psi \gamma$ decay determines $C = +$ (4.4σ observation)
- Angular distributions support $J^{PC} = 1^{++}$;
 2^1P_1 is too massive, especially if $Z(3931)$ is 2^3P_2

If not charmonium ...

- s -wave cusp at $D^0 \bar{D}^{*0}$ threshold Bugg
- $D^0 - \bar{D}^{*0}$ “molecule” bound by pion exchange Tørnqvist, Swanson
- Diquark–antidiquark “tetraquark” state $[cq][\bar{c}\bar{q}]$

Distinctive Predictions?

- Threshold bumps at all thresholds (?) no excitations
- No pion exchange for $D_s \bar{D}_s^* \rightsquigarrow$ no analogue molecule
- Tetraquark interpretation suggests split $X(3872)$ and excited states
- What happens in the $b\bar{b}$ system?
- If a dynamical level and a threshold coincide? Braaten & Kusunoki

For quarkonium:

Increasing effectiveness of lattice QCD (below threshold)
influence of gluons, ...

Davies

Coupled-channel potential models are useful interpretive tools

Experiment – Theory Dialogue

BaBar suggestion (inconclusive but provocative) (hep-ex/0507090):

$$B^- \rightarrow K^- X(3872) \quad 61.2 \pm 15.3 \text{ events} \quad 3871.3 \pm 0.6 \pm 0.1 \text{ MeV}$$

$$B^0 \rightarrow K^0 X(3872) \quad 8.3 \pm 4.5 \text{ events} \quad 3868.6 \pm 1.2 \pm 0.2 \text{ MeV}$$

$$\Delta M = \quad 2.7 \pm 1.3 \pm 0.2 \text{ MeV}$$

Tetraquark: two states, $\Delta M \approx 7 \text{ MeV}$

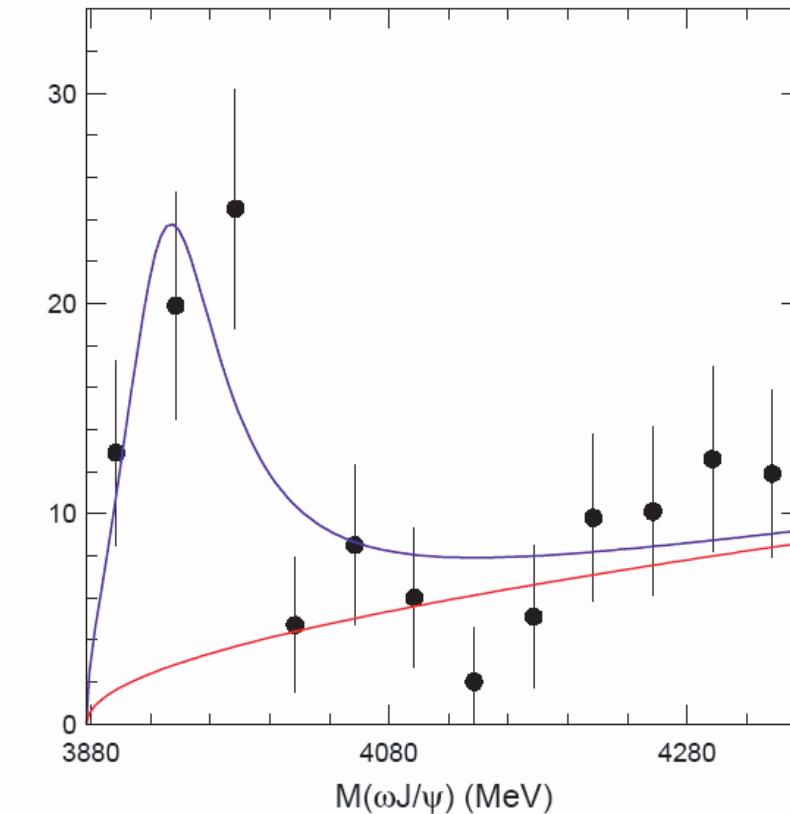
$$\mathcal{R} \equiv \frac{\mathcal{B}(B^0 \rightarrow K^0 X(3872))}{\mathcal{B}(B^- \rightarrow K^- X(3872))} = 0.50 \pm 0.30 \pm 0.05$$

Tetraquark: $\mathcal{R} \approx 1$; Molecule: $\mathcal{R} \lesssim 0.1$

But wait, there's more!

Belle: “strong, near-threshold enhancement” in $B \rightarrow K\omega J/\psi$

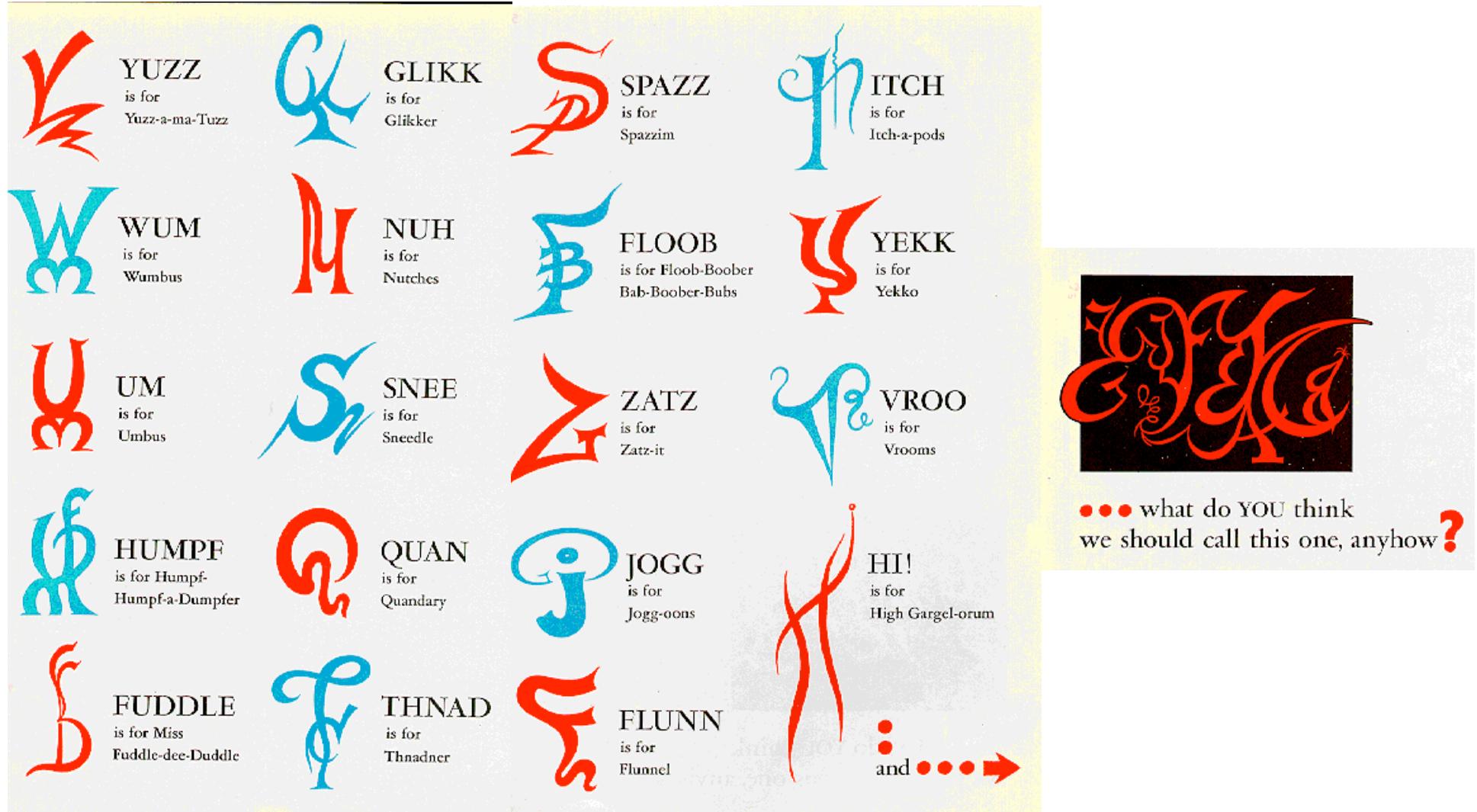
Mass ≈ 3940 MeV, Width ≈ 92 MeV



No obvious charmonium candidate

New States Associated with Charmonium

- $\eta_c'(3637)$: 2^1S_0
- $h_c(3524)$: 1^1P_1 CLEO (E835)
- $X(3872)$: $J^{PC} = 1^{++}$, *probably not charmonium*
- $Y(3940 \pm 11)$: seen in $B \rightarrow K\omega J/\psi$; $\Gamma = 92 \pm 24$ MeV Belle
- $X(3936 \pm 14)$: seen in $e^+e^- \rightarrow J/\psi + X$ Belle, hep-ex/0705019
 $\Gamma = 39 \pm 24$ MeV; $\rightarrow D\bar{D}^*$, $\not\rightarrow D\bar{D}$ $\eta_c''(3^1S_0)$ candidate
- $Z(3931 \pm 4 \pm 2)$: seen in $\gamma\gamma \rightarrow D\bar{D}$ Belle, hep-ex/0507033
 $\Gamma \approx 20$ MeV, consistent with 2^{++} $\chi_{c2}'(2^3P_2)$ candidate
- $Y(4260)$: 1^{--} seen in $e^+e^- \rightarrow \gamma\pi^+\pi^-J/\psi$ BaBar, hep-ex/0506081
 $\Gamma \approx 50 \sim 90$ MeV; also in $B \rightarrow K^-J/\psi\pi\pi$ hep-ex/0507090



Dr. Seuss, *On Beyond Zebra*

(More Charmonium Levels to Be Found)

- $\psi_2(3831)$ ($1^3D_2:2^{--}$) $\rightarrow \gamma\chi_{c1,2}, \pi\pi J/\psi, \not\rightarrow D\bar{D}$
- $\eta_{c2}(3838)$ ($1^1D_2:2^{-+}$) $\rightarrow \gamma h_c, \pi\pi\eta_c, \not\rightarrow D\bar{D}$
- $\psi_3(3868)$ ($1^3D_3:3^{--}$) $\rightarrow D\bar{D}, \Gamma \lesssim 1$ MeV
- $\psi_4(4054)$ ($1^3F_4:4^{++}$) $\rightarrow D\bar{D}, \Gamma \lesssim 5$ MeV
- (not to mention hybrid $c\bar{c}g$ levels)

D_{sJ} Levels

- ▷ Two states well established, properties converging
 J^{PC} seem consistent with $j_q = \frac{1}{2}$ $c\bar{s}$ levels,
but centroid well below $j_q = \frac{3}{2}$, so quite narrow
disagrees with relativistic potential models

$0^+ : D_{sJ}^*(2317) \rightarrow D_s\pi^0$; $1^+ : D_{sJ}(2460) \rightarrow D_s\gamma, D_s^*\pi^0$
 $1^+ : D_{s1}^*(2536)$; $1^+ : D_{s2}^*(2573)$

Is there a simple, graceful interpretation?

$c\bar{s}$ or DK or tetraquark

Radiative decays to distinguish

What happens in B_s system?

A New Element?

- ▷ Could chiral symmetry and confinement coexist?
 - Expect chiral supermultiplets: states with $L, L + 1$, same j_q :
 - $j_q = \frac{1}{2}$: 1S(0^- , 1^-) and 1P(0^+ , 1^+)
 - $j_q = \frac{3}{2}$: 1P(1^+ , 2^+) and 1D(1^- , 2^-)
 - Hyperfine splitting $M_{D_s(1^+)} - M_{D_s(0^+)} = M_{D_s(1^-)} - M_{D_s(0^-)}$
 - Predictions for decay rates match experiment (so far)
 - How far is QCD from this situation?

Bardeen, Eichten, Hill, PRD **68**, 054024 (2004)

Hadron physics is rich in opportunities

- ▷ Models are wonderful exploratory tools
- ▷ Make contact with lattice, symmetries at every opportunity
- ▷ Build coherent networks of understanding
- ▷ Tune between systems: models beyond their comfort zones
- ▷ Relate mesons to baryons (quarks to diquarks?)
- ▷ Look beyond qqq and $q\bar{q}$:
exotics, matter under unusual conditions

Focus on what we can learn of lasting value